swiss physical society

Nr. 64, Mai 2021

SPG Mitteilungen
Communications de la SSP

Auszug - Extrait

Progress in Physics (81)

Superconductivity – Current State, Records, and new Frontiers

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Introduction

In the past five years, a sequence of breakthrough experiments has pushed the record for highest transition temperature for superconductivity. Hydrogen compounds, stabilized by hydrostatic pressure comparable to that found in the center of the earth, were found superconducting at unprecedentedly high temperatures [1-3]. Last year, this research culminated with the finding of room-temperature superconductivity in a carbonaceous sulfur hydride compound [4]. This fascinating discovery provides the third high-temperature superconductor system found in the last three decades. Compared to the previous discoveries, these new high-temperature superconductors are surrounded by much less mystery and controversy. Motivated by these fascinating developments, we here take stock of the state of superconductivity, a field with a rich history in Switzerland [5], and present current and future directions.

Background

Until recently, the history of superconductivity could roughly be divided into three periods. The first, starting from the discovery of superconductivity by Kammerlingh-Onnes (1911), was characterized by experimental and theoretical grope until a smoking gun experiment revealed a connection between phonons, in other words lattice vibrations, and superconductivity. This led to the formulation of a microscopic theory of superconductivity by Bardeen, Cooper and Schrieffer (BCS theory, 1957) [6]. The BCS theory and its strong-coupling extensions provided an incredibly successful framework and ushered in a second era, the BCS era of conventional superconductivity. With the exquisite understanding, important applications such as medical scanning devices and superconducting quantum interference devices (SQUID) based on the Josephson effect were developed. A further central result of the BCS theory is that the superconducting transition temperature is proportional to the Debye frequency (complicated by the fact that the superconductivity also depends exponentially on electron-phonon coupling and electronic density of states). This led to the notion of a maximally reachable T_c in phonon-mediated superconductors, often put at around 30 Kelvin. The second era lasted until the end of the 1970s, when unconventional superconductivity was discovered in $CeCu_2Si_2$ by F. Steglich [7]. This latest era, lasting until this date, became eminent by the discovery of high-temperature superconductivity in the cuprates by the Swiss “tandem” Bednorz and Müller (1986) [8]. The era of unconventional superconductivity, however, brought the field back to groping in the dark. Unconventional superconductivity has turned out to be an exquisitely difficult problem. Still, the research into understanding known and finding novel unconventional superconductors has led to many important developments in both theoretical and experimental physics over the past decades.

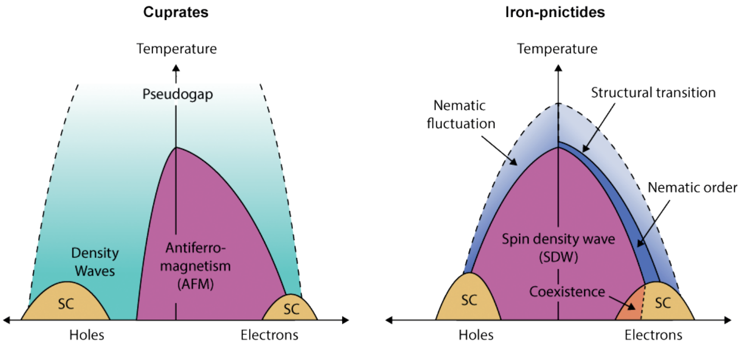

Figure 1: Schematic phase diagrams of copper-oxide (cuprate) and iron-arsenide (pnictide) superconductors – with courtesy of Jaewon Choi (Diamond Light Source - UK). In both systems, domes of superconductivity emerge in vicinity to antiferromagnetic states. The pseudogap phase in the cuprates and the nematic order in the pnictides are being investigated just as much as superconductivity itself.

Superconductivity in magnetic systems — the Copper age

Unconventional superconductivity is often found in near vicinity to magnetically ordered states [9]. High-temperature superconductivity in layered copper oxide materials is, for example, established by hole doping a Mott insulating antiferromagnetic phase – see Figure 1. In these materials, superconductivity appears in a ‘dome’ between an antiferromagnetic insulating state and a conventional Fermi liquid metal. While BCS theory might still apply, superconductivity in the cuprates is most likely not driven by lattice vibrations [10].

BCS theory explains superconductivity by bosonic pairing of electrons near the Fermi level, which opens a gap around the Fermi level. When mediated by lattice vibrations, this gap is generically isotropic. In the cuprates, by contrast, the gap is found to have symmetry-imposed nodes [11]. This is expected for pairing mediated by electron interactions with antiferromagnetic excitations. A lot of effort has therefore been invested into studying antiferromagnetic spin excitations. At the Paul Scherrer Institute (PSI), for example, Resonant Inelastic X-ray Scattering instruments (RIXS) [12] have been designed to study such excitations.

Iron age

In the period 2006-2008, superconductivity in another magnet system (Figure 1), namely in iron-based materials, was discovered [13]. Just like with the cuprates, the transition temperature quickly surpassed what is expected from lattice-vibration-mediated superconductivity. Furthermore, with superconductivity emerging in a dome around a putative spin-density-wave quantum critical point, magnetism is again in contention [14]. Unlike in the cuprates, the gap structure in most iron-based superconductors has no symmetry-imposed nodes, but changes its sign between different (disconnected) parts of the Fermi surface. The novel aspect of multiple bands has led to an explosive amount of work in the last decade to characterize magnetic, orbital, and electronic degrees of freedom and their entanglement in these superconductors.

Exotic and topological superconductivity

While the high-temperature superconductors with their promise of room-temperature superconductivity occupied much of the community for more than 25 years, a lot of focus has shifted to different aspects of unconventional superconductivity in recent years. This shift is supported by the realization that the advantages of quantum technologies warrant the large effort of cooling to only a few Kelvin, thus rendering the transition temperature less crucial. Of particular interest are topological superconductors with their potential application in (topological) quantum computation, but also other exotic (low-temperature) superconductors provide formidable properties – and puzzles.

An example is the realization of spin-triplet superconductivity mediated by a ferromagnetic pairing mechanism, which could result in a chiral and hence, topological state. For many years, Sr_2RuO_4 was a prime candidate and experimental evidence pointed to a triplet pairing mechanism [15,16] and broken time-reversal symmetry [17]. However, the evidence for triplet pairing has been challenged by more recent experiments [18] and the field is back to the “drawing board”. It is, however, generally agreed that superconductivity in this ruthenate material cannot be explained within the BCS lattice-vibration formalism. The Sr_2RuO_4 compound is one of a handful (URu_2Si_2, UPt_3, UTe_2 [19]) of exotic superconductors. Many of these exotic superconductors are found in so-called heavy fermion materials, where Kondo physics of the *f*-electron is important.

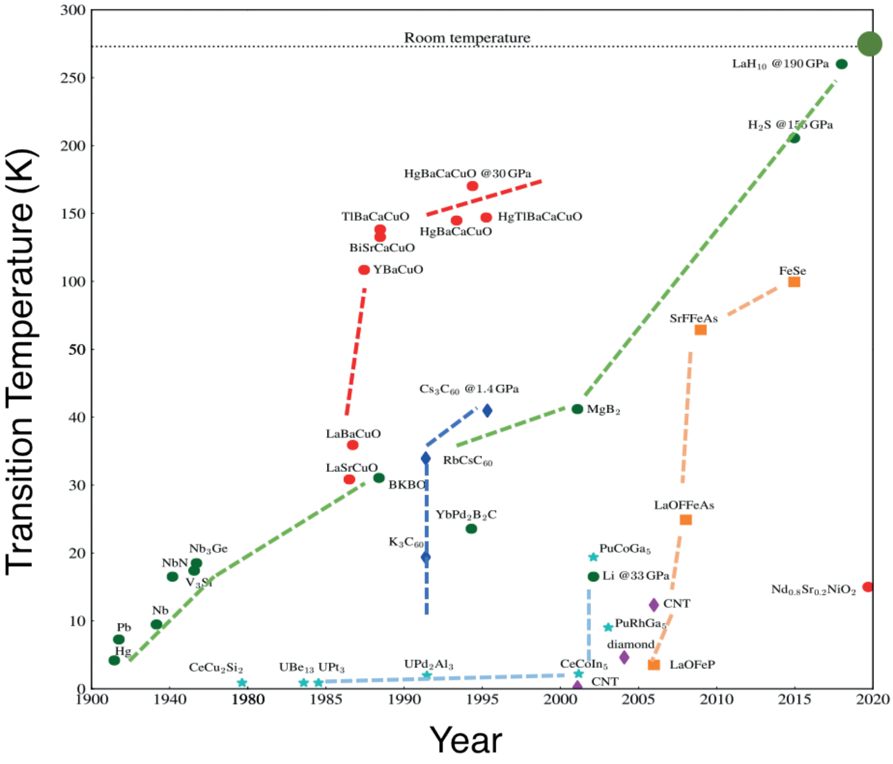

Figure 2: History of superconductivity – transition temperature versus year of compound discovery. Notice that the time axis, the periods 1900-1980 and 1980-2020 have difference scales to proportionally reflect the number of discoveries. The color code reflects different classes of superconductivity.

Magic twists and diluted superconductors

The electronic properties of graphene have been in the center of a booming field recognized by the 2010 Nobel Prize. An interesting theory prediction was that twisted bilayer graphene is the setting for magic angles with high electronic density of states [20]. The experimental realization led to the discovery of gate-controlled superconductivity [21]. Although both the carrier density and superconducting transition temperature are low, many electronic properties resemble what has been found in the high-temperature superconductors. Researchers are therefore debating about the right framework for superconductivity in magic-angle twisted bilayer graphene. Another debate is how much carrier dilution a superconductor can tolerate. Remarkably, the Behnia group demonstrated that one electron per hundred thousand unit formular of $SrTiO_3$ is enough to support superconductivity [22].

Conventional high-temperature superconductivity

That the theorized upper bounds for the critical temperature in phonon-mediated superconductors were not set in stone first became apparent when superconductivity was found at 39 K in MgB_2 20 years ago [23,24]. Additionally, it was long expected that light elements with large Debye frequencies would be a route to high-temperature superconductivity [25]. Hydrogen is the lightest element but solidifies only upon application of very large hydrostatic pressures [26]. In 2015, a German research team led by M. Eremets, managed to crystalize HS_2 (using large pressure) and demonstrated a record-high transition temperature just above 200 K [1]. This breakthrough inspired new predictions based on the BCS framework and in 2019 experiments confirmed superconductivity in LaH_{10} just below 250 K [2,3]. More recently, room-temperature superconductivity (see Figure 2) was realized for the first time in carbonaceous sulfur hydride material exposed to huge hydrostatic pressure of more than 250 GPa [4]. A major drawback of the high-pressure conditions is their impediment for quick and widespread reproduction of the experiments and the comprehensive characterization of the superconducting state.

Nevertheless, these results present a major achievement and researchers are now searching for superconducting light-element compounds that are stable under ambient conditions.

Summary and outlook

While Andreas Schilling and Hans Rudolf Ott are still holding the record for finding the highest superconducting transition temperature under ambient condition [27], room temperature superconductivity is now realized in light-element compounds under large pressure. Superconductivity has passed its hundred-year anniversary, but more than ever is a field full of unexpected surprises. The complexity surrounding many-body quantum physics is at the same time the source of seemingly slow progress and the ingredient generating a constant flow of new discoveries. Unpredictability and serendipity are blessed. Only certainty is that last word has not been written on superconductivity.

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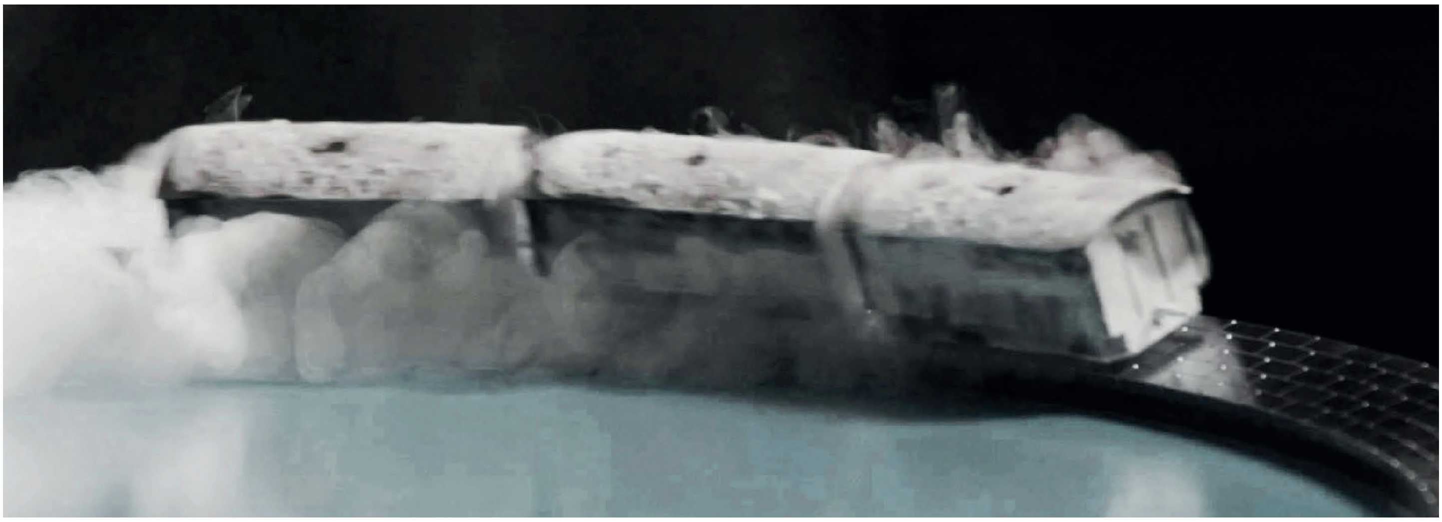

Levitating superconducting train at the Science Exploratorium UZH